Ain Shams University
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Wind Energy Electric Generation and Integration with Large Networks.

M.Sc Thesis

By

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Statement

This dissertation is submitted to Ain Shams University in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering.

The work included in this thesis was carried by the author in the department of Electrical Power and Machines, Ain Shams University.

No part of this thesis has been submitted for a degree or a qualification at any other university or institution.

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Abstract

One of the earliest sources of power used by man is the wind turbine. Wind turbines have been documented to be in use for more than 1000 years now. The earliest wind turbine designs were extremely simple. Turbines were allowed to rotate at speeds depending on the velocity of the wind. Wind turbines had served mainly in grain grinding and water pumping. Presently, wind energy has become an important source of non-polluting renewable energy for the generation of electric power.

For electrical wind projects, the value of wind energy in a site is determined by two key parameters, the “Shape factor” and the “Scale factor”. These two factors are functions of the mean wind speed, and the speed standard deviation over a certain period of time, respectively.

This energy is transformed into electrical energy through the use of wind turbines and electric generators. To maximize the captured energy, certain control strategies are needed to accomplish the ideal power curve. Two main controls are addressed: Blade pitch control and Rotor Speed Variability control. In most cases, on the generating level, the generated electric energy is fed into the electric supply grid in one of many different ways. Among these, power is fed to the grid either by stator controlled or rotor controlled doubly-fed induction generators.

Wind turbines are dependent upon airflows, which are themselves subject to weather conditions and local effects. This results in corresponding variations in the primary energy supply over which the turbines have no control. Output can only be changed by reducing (or increasing) power generation. The grid is therefore not only influenced by fluctuations in the power consumption side, but also -in the case of uncoordinated feed from wind turbines- by the effects of the weather on the energy supply. The effects of wind turbines on the grid and the power that can be drawn or supplied are determined primarily by the type of control and

voltage levels. Changes and periodic fluctuations in short-circuit power and voltage must be taken into account, as well as any asymmetries in the network or load.

The economic aspects of energy generation play a key role in the selection of an energy option, as well as its technical feasibility. Three techniques have been discussed in the evaluation of the economic feasibility of wind farms, namely: The Net Present Value method, Benefit/Cost Ratio method, and Payback Period method. The financial benefit is essentially produced by the sale of the generated electric energy.

The above technical and economic analyses have been applied to the Zafarana wind farm in Egypt. Special reference to two types of the turbine-generator units of this large wind farm, were thoroughly examined. The analysis of this case study proposes the possible expansion in the energy generated by this wind farm at economically viable rates. The case study has revealed good results with respect to both technical and economic aspects.

List of Symbols

A_D $Area\ of\ the\ actuater\ disc$

B $constant$

B_A $Benefit$

C_F $Capacity\ Factor$

C $Cost$

E_D $Energy\ Density$

E_I $Energy\ Intensity$

E_V $Energy\ Produced\ at\ certain\ speed$

F $Cumulative\ Distribution$

I_{an} $Starting\ Current$

I_N $Nominal\ Current$

NPV $Net\ Present\ Value$

$P(\ )$ $Probability\ function$

P_V $Power\ available$

RCF $Rough\ Capacity\ Factor$

S_k $Short\ Circuit\ power$

T $time$

T_g $Torque$

U $volt$

V_{Fmax} $most\ frequent\ wind\ speed$

V_{Emax} $velocity\ producing\ maximum\ Energy$

V_I $cut\ in\ wind\ speed$

V_R $rated\ wind\ speed$

V_O $cut\ out\ wind\ speed$

V_m $mean\ wind\ speed$

X $any\ variable$

$X_d^{"}$ *subtransient reactance*

Z *grid impedance*

a *constant*

b *constant*

c *scale factor*

c *magnification factor*

k *shape factor*

f_i *frequency distribution*

$f(V_i)$ *probability distribution function*

n *number of samples*

p_D^+ *atmospheric pressure in front of the actuater disc*

p_D^- *atmospheric pressure behind the actuater disc*

x *variable*

$x_d^{"}$ *subtransient factor*

Γ *Standard gamma function*

Ω *rotational speed*

σ_V *Standard deviation*

μ_2' *Second raw moment*

ρ_a *air density*

λ *tip speed ratio at different conditions*

Table of Contents

1 Chapter One - Introduction

One of the earliest sources of power used by man was the wind turbine. Wind turbines have been in documented use for more than 1,000 years. The earliest wind turbine designs were extremely simple; turbines were allowed to rotate at a rate proportional to the velocity of the wind. They were used to pump water, grind grain, cut lumber, and perform a myriad of other tasks.

The cost of crude oil has doubled within the past years from 25$/bbl to 50$/bbl and a new peak of 70$/bbl. The price of gas has followed the same trend which has a fundamental impact on the cost of generating electricity [1].

Electricity systems-supply and demands are inherently highly variable, and are influenced by large number of planned and unplanned factors. The changing weather makes millions of people switch on and off heating, lighting and they switch on and off equipment that demands instant power, lights, TVs, computers.

The system operators need to balance out planned and unplanned changes in constantly changing supply and demand in order to maintain the system's integrity. Both electricity supply and demand are variable. The issue, therefore, is not one of variability or intermittency, but how to predict, manage and ameliorate variability and what tools can be utilized to improve efficiency.

Wind power is variable in output but the variability can be predicted to a great extent. This does not mean that variability has no effect on the system operation. It does, especially in systems where wind power meets a large share of electricity demand.

Wind power is sometimes incorrectly considered as intermittent energy source. This is misleading. At power system level, wind power does not start and stop at irregular intervals (which is the meaning of intermittent).

It is also worthwhile considering that the technical availability of wind turbines is at a very high level (98%), compared to other technologies. The term intermittent is inappropriate for system wide wind power and the qualifier 'variable-output' for wind power should be used. On the other hand, the system is prepared to deal with intermittencies such as outages of conventional plants and line faults.

For thermal-generating plants the loss due to unplanned outages represents on average 6% of their energy generation. Detailed analysis shows that the forced outage rate of fossil plants represents at least 10%. Thus, unplanned outages of conventional plants occur frequently. In general these forced outages are not predictable, with high gradient from full power to zero power.

The early twentieth century saw the start of the electric era. The rapid advances in motor, generator, lighting, and appliance designs by Edison, Steinmetz, Tesla and others offered the promise of an electric-powered utopia. As early as 1888 the Brush wind turbine in Cleveland, Ohio, had produced 12 kilowatts of direct current (DC) power for battery charging at variable speed. DC and variable-speed wind turbines seemed only natural. Many early electric motors required direct current and the varying voltage due to turbulent winds were held relatively constant by the associated battery bank. At remote farms, where power lines might never reach, a DC wind turbine could charge batteries, and operate equipment that could never cope with varying alternating current (AC) frequencies caused by constantly changing wind speeds.

In 1925, Marcelleus and Joseph began work on the first truly high-speed, small-size, affordable battery-charging turbine. Thousands of their 32 Volt and 110 Volt DC machines were manufactured starting in the late 1920's and running into the 1950's. This machine was followed by others such as the “Windcharger”. They could be set up easily and required little maintenance. All of these machines were allowed to run at variable speed. Even after AC utility power had begun to spread through cities and towns, Sears Roebuck and others, manufactured and distributed a wide range of products designed to run on DC to satisfy the needs of remote farms and ranches using batteries and variable-speed DC turbines.

In 1937 the creation of the Rural Electric Associations started the demise of these stand-alone variable-speed DC machines. As AC power lines spread throughout rural America, the need for such machines began to fade.

America was becoming connected, and in the future would depend upon large central power plants to produce electricity for all. Long transmission lines required much higher voltage for efficient distribution. Electric transformers and their required alternating current were the obvious technology to employ. It was then necessary to standardize on constant voltage levels and a constant frequency. In North America, this fixed frequency became 60 hertz.

Despite the apparent difficulties of connecting a wind turbine to the AC electrical grid, as early as 1939 in the United States, such a step had been explored. Even earlier examples of large turbines used to produce electricity tied to an established AC electrical grid may be cited; however, for depth of engineering and breadth of vision, few early pioneers have surpassed Palmer Putnam's Grandpa's Knob machine. This machine was incredibly advanced for its day, with full-span pitch control, active-yaw drive, two-bladed flapping rotor, and 1.25 MW rating. However, the Smith-Putnam turbine rotor avoided the problem of variable speed and run at a fixed rpm locked to a synchronous generator directly tied to the electrical grid. However, by fixing the rotational rate of the turbine to that of the electric grid, the turbine lost a great deal of wind potential.
Allowing the machine to rotate at a varying rate would optimize the aerodynamics of the rotor by allowing its speed to be proportional to wind speed. In this operating mode the machine can capture the maximum fraction of available wind energy. Not only would it gain more aerodynamic efficiency in high winds, but it would also be able to run at lower speeds and gather more energy than a fixed-speed machine.

The dream of a variable-speed wind turbine tied to the AC electrical grid began to become a viable reality in the early to mid-1970. Machines went on-line in the United State and Europe, using several different methods for transforming variable-voltage, variable-frequency outputs to reliable constant-voltage, constant-frequency outputs. In addition to large grid-connected machines, small stand-alone machines were developed that incorporated these new technologies and would allow the farmer or homeowner to produce his own power, and to someday allow him to sell his excess power back to the utility grid. For example, the 8-kW Windworks machine of the early 1970's used a diode bridge to rectify the variable-frequency output of the permanent magnet generator. Silicon controlled rectifiers (SCRs) were used in an inverter module to convert the resulting rectified DC output to AC synchronized to the grid. Technologies like these are still in use and are being further developed. New technologies are under constant development.

2 Chapter Two - WIND FARM ANALYSIS

2.1 Wind Energy Analysis

For estimating the wind energy potential of a site, the wind data collected from the location should be properly analyzed and interpreted. Long term wind data from the meteorological stations near to the candidate site can be used for making preliminary estimates. This data, which may be available for long periods, should be carefully extrapolated to represent the wind profile at the potential site. After this preliminary investigation, field measurements are generally made at the prospective location for shorter periods. One year wind data recorded at the site is sufficient to represent the long term variations in the wind profile within an accuracy level of 10 per cent [2].

Modern wind measurement systems give us the mean wind speed at the site, averaged over a pre-fixed time period. Ten minutes average is very common as most of the standard wind analysis software is tuned to handle data over ten minutes. This short term wind data are further grouped and analyzed with the help of models and software to make precise estimates on the energy available in the wind. The data are grouped over time spans in which we are interested in. For example, if we want to estimate the energy available at different hours, then the data should be grouped in an hourly basis. The data may also be categorized on daily, monthly or yearly basis.

2.1.1 AVERAGE WIND SPEED

One of the most important information on the wind spectra available at the location is its average velocity. In simple terms, the average velocity (V_m) is given by:

$$V_m = \frac{1}{n}\sum_{i=1}^{n} V_i \quad \text{.. (2.1)}$$

Where V is the wind velocity and n is the number of wind data.

However, for wind power calculations, averaging the velocity using equation (2.1) is often misleading. For example, 1 hour wind data from a site collected at 10 minutes interval are shown in table1. As per equation (2.1), the hourly average wind velocity is 6.45 m/s, taking the air density as 1.24 kg/m3, the corresponding average power is 166.37 W/m2. If we calculate the power corresponding to individual velocities and then take the average, the result would be 207 W/m2. This means that, by calculating the average using equation (2.1), we are underestimating the wind power potential by 20 per cent [2].

***Table 1** Wind velocity at 10 minutes interval collected from the site*

NO	V, m/s	V^3	P , W/ m^2
1	4.3	79.51	49.29
2	4.7	103.82	64.37
3	8.3	571.79	354.51
4	6.2	238.33	147.76
5	5.9	205.38	127.33
6	9.3	804.36	498.7

For wind energy calculations, the velocity should be weighted for its power content while computing the average. Thus the average wind velocity is given by:

$$V_m = [\frac{1}{n}\sum_{i=1}^{n} Vi^3]^{1/3} \text{...} (2.2)$$

If we use equation (2.2), the average velocity in the previous example is 6.94m/s and the corresponding power is 207 W/m2. This shows that due to the cubic velocity-power relationship, the weighted average expressed in equation (2.2) should be used in the wind energy analysis.

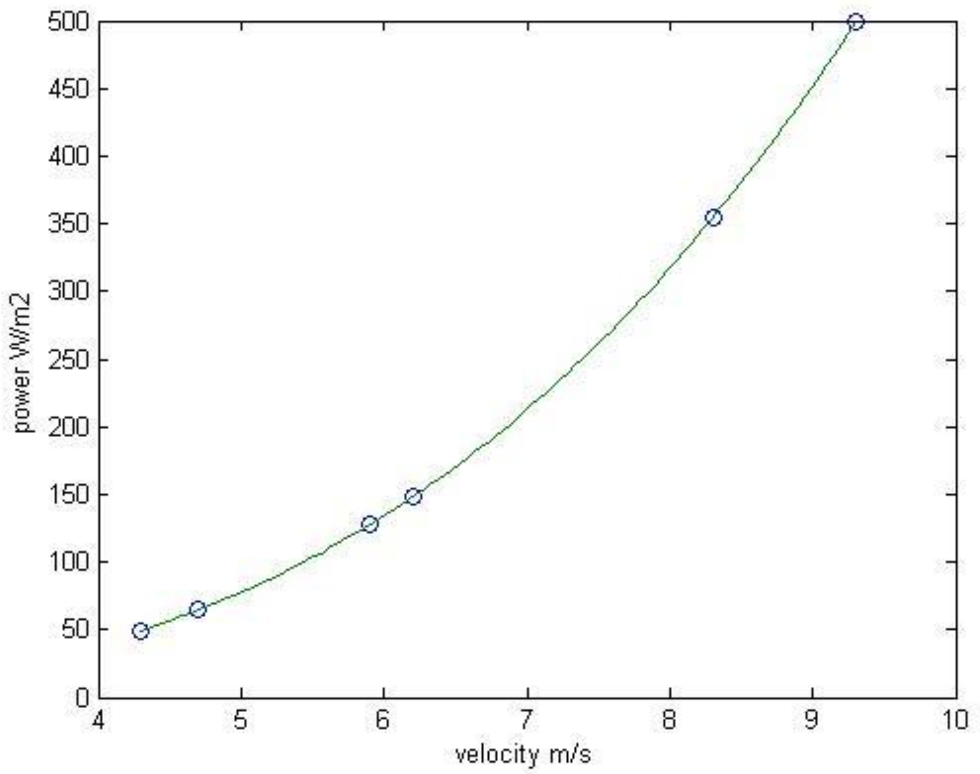

***Fig.2.1**. the cubic relation between velocity and power*

```
v=[4.3 4.7 8.3 6.2 5.9 9.3]
vn=(v.^3)
v1=sum(vn)
v1=sum(single(vn))
```